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A Study of Solar Hard X-ray Albedo Sources

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ABSTRACT

The diffuse solar X-ray albedo flux, formed from primary-source 10-100 keV X-rays that backscatter from the solar photosphere, represents a significant component of the observed X-ray flux. As such it both distorts the spectral interpretation of X-ray emission and offers a potentially powerful, but hitherto unused, diagnostic of electrons accelerated in solar flares. This proposal uses the unique capabilities of the Ramaty High Energy Spectroscopic Imager (RHESSI) to isolate this albedo component, determine its properties such as flux, size, shape and centroid location as a function of time and energy. The results will be used to evaluate corrections to photon spectra for the intermingled contribution of primary and albedo sources, to measure the primary source height as a function of time and energy, and to provide a new diagnostic for the evaluation of electron beaming and directivity.

PROJECT DESCRIPTION

1 Introduction

Solar flares provide a close-up view of particle acceleration and impulsive energy release, processes which are fundamental to many areas of space physics. One of the most direct signatures of the acceleration and transport of electrons in flares is provided by hard X-ray emission. These electrons produce bremsstrahlung radiation when they interact with the denser parts of the solar atmosphere. The resulting spectra and images can be interpreted to provide direct spectral, spatial, and temporal signatures of the accelerated or heated electron component in the context of their magnetic environment.

In the decade preceding 2002, the Yohkoh HXT and SXT instruments have painted a broad picture of the flare process. Since then, the RHESSI satellite has improved on that picture with its improved sensitivity and high spectral and spatial resolution (Lin *et al.*. 2002). The high energy electrons have been placed in context by comparison of hard X-ray spectra and images with those of TRACE, the SOHO instruments (EIT, CDS, MDI, LASCO), ground-based magnetographs and radio interferometers.

These collaborative observations have permitted great improvements in the quantitative knowledge of electron energetics, and it is now become possible to determine the electron energy spectrum as a function of time, energy, and position in a wide variety of flares. This has provided information on the accelerated electron spectrum and has demonstrated that the energy of the accelerated electrons to tens of keV can be comparable to the total flare energy. This shows that electron acceleration is a major part of the basic energy release process. Nevertheless, in spite of many advances in our understanding, there are significant deficiencies in our knowledge of the shape of the electron momentum distribution (*e.g.*, does it have low energy cutoffs, and what is its angular distribution about the field line to which it is confined?) and the three-dimensional distribution of the accelerators and sources (*e.g.*, what are the heights and the sizes of the coronal, ”loop-top”, and ”foot-point” components of flares?) The answers to these questions are important for several reasons. The low-energy cutoffs inferred from high-resolution photon spectra are crucial to the overall flare energetics; the pitch-angle distribution is a largely unknown factor required for understanding of accelerationn and energy transport; and source heights are essential for creating a three-dimensional picture of transport in the context of coronal magnetic fields.

One aspect of flare X-ray emission that has not drawn proper attention since the launch of RHESSI is the “albedo”, which is the portion of the X-ray flux that is back-scattered from the photosphere. These regions of reflected X-rays represent 20-50% of the X-ray flux in every solar flare and are rich in information useful for flare physics. With a different approach to analyzing existing data from the RHESSI mission, the albedo component of the X-ray emission can be isolated and used to address a number of important questions. In subsequent sections, we outline this new approach and indicate how the albedo can be used.

2 A New Approach

The RHESSI instrumentation consists of a set of nine rotating modulation collimators which encode the spatial information on the source by rapidly time-modulating the observed X-ray count rates. Germanium detectors behind each collimator provide high spectral resolution for either spatially-integrated spectroscopy or for energy-specific imaging.

The conventional approach to RHESSI imaging spectroscopy of hard X-ray flares is to reconstruct images using one of the RHESSI standard imaging algorithms such as Back-projection, Clean, MEM, Pixons. (See Hurford, Schmahl et al, 2002 for a discussion of these methods.) The results are displayed as maps at one or more selected energies. These maps typically show one or more discrete, compact sources. Comparing maps at multiple energies yields spectra for individual compact source components. Because of their low surface brightness, however, large diffuse sources cannot be seen in such maps. Although this current "default" mode of RHESSI data analysis neglects diffuse sources, their flux can be a large fraction of that of the compact source flux.

Nevertheless, diffuse sources exist. They arise because individual hard X-rays emitted by the primary sources of solar flares have a high probability of being Compton scattered off the photosphere. The flux of these back-scattered X-rays, called "albedo", can comprise $\sim 20-50\%$ of the flux of the primary source, and so it is a non-negligible fraction of the total emission (Tomblin 1972; Santangelo *et al.* 1973, Brown, van Beek and McClymont 1975; Bai and Ramaty 1978). The albedo spectrum differs from the primary source spectrum, but the two are intermingled in the total flux.

The study of albedo provides the observer with a distinct perspective and unique diagnostics. First, isolation of the albedo flux from the total flux permits a vital correction (Alexander & Brown, 2002) to the flare photon spectrum, essential for inferring the electron energy distribution. Second, the size of an albedo patch below the primary source in a flare gives a direct measure of the height of the flare (Brown and Van Beek 1975, Brown *et al.* 1975). Third, the centroid location and size of the albedo patch give independent information about directivity of the downward-directed X-ray photons. Conventional corrections for spectra using models of albedo assume isotropy of the X-rays from the primary source. This is done for simplicity in the absence of good evidence to the contrary, since there are arguments both for and against the existence of anisotropy and directivity (Brown, 1975; Henoux 1975; Langer & Petrosian, 1977; Bai & Ramaty 1978.) Using parameters found for the albedo we will check the appropriateness of the isotropy assumption, and we will be able to guide analysis towards improved corrections.

3 Why albedo hasn't been imaged and how we will exploit it

Although it is difficult to image or display these diffuse sources by conventional means, RHESSI's indirect (Fourier-based) imaging technique is ideally suited to the isolation of the diffuse albedo component and to the determination of its basic properties such as its spectrum, size, shape and centroid location relative to the primary source.

Figure 1 shows a schematic example of the distribution of photons ($\sim 12-50$ keV) from a primary source and the albedo source. For simplicity, the primary source is modeled by a Gaussian. (This turns out to be a good approximation for the main phase of many flares, as found by Schmahl and Hurford 2002, 2003). The flare is taken to be at a longitude of 70°, and the albedo's centroid is

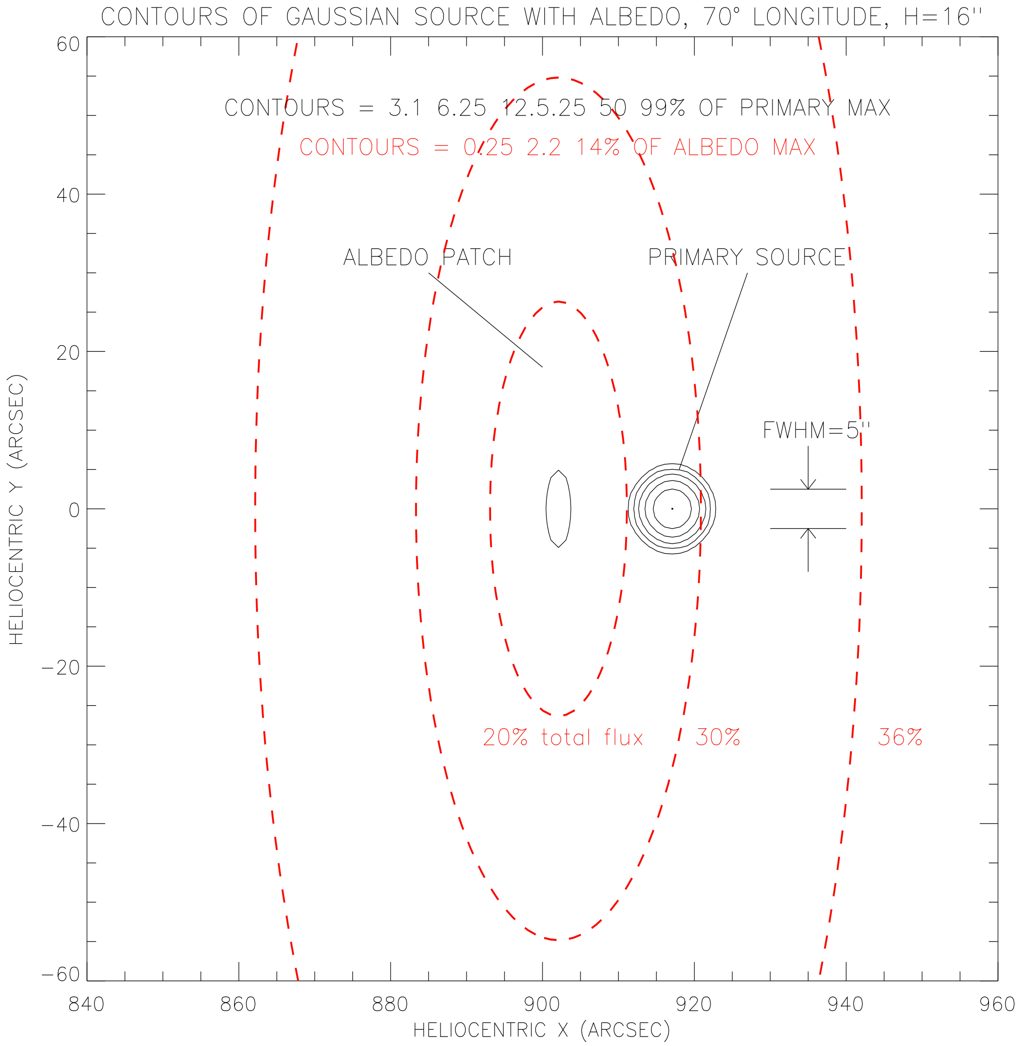

Figure 1: Solid contours (black) show what conventional imaging sees of a primary source and its albedo (factor of 2 intensity levels), where the albedo patch contains 40% of the total flux. The dashed contours (red) show the intensity boundaries that contain 20, 30 and 36% of the total flux. The primary source is taken to be a Gaussian, FWHM=5´´, at a height of 12 Mm, and a longitude of 70°. At the 20% level, the albedo patch has a long-axis width of 50´´ and a short-axis width of 18´´. The horizon distance at the primary source is 175´´. Note that the peak brightness of the albedo patch is $\sim 3\%$ of the primary source, too low for direct imaging methods.

therefore displaced inward from the primary source. At such a longitude, the transverse displacement of the albedo centroid is 94% of the true height of the primary source above the photosphere. In general, the albedo patch can cover an area up to the horizon of the photospheric area that can be "seen" from the primary source. The long axis of this patch is thus as large as $\sqrt{2h \cdot R_\odot}$, where h is the height of the primary source above the photosphere. For anisotropic X-rays and/or scattering the value may be smaller, but it is always proportional to $\sqrt{h}$, so it is possible to infer h from the size of the albedo patch.

The actual distribution of back-scattered X-rays depends on their energy and direction. This distribution, as computed by Bai and Ramaty and others, is not so important as the fact that the 50% contour of the albedo patch is large compared to the size of the primary source. For the case of isotropic scattering (à la Brown *et al.* 1975) and a source height of 11 Mm, assumed for this schematic example, the albedo patch is found to be $\sim 50''$ in diameter, much larger than the primary source (here, taken to have FWHM=$5''$). The fact that the albedo source can be almost an order of magnitude larger than the primary source implies that its surface brightness is two orders of magnitude fainter. It also provides the basis of its isolation by RHESSI's imaging technique. Specifically, RHESSI's intermediate and fine grids modulate only the compact primary source whereas RHESSI's coarsest grids modulate the primary plus albedo sources.

3.1 Specifics of RHESSI's use of Fourier techniques for studying albedo

The RHESSI instrumentation is uniquely suited for studying these diffuse sources in the range where albedo is important (15-50 keV), due its use of Fourier techniques for the determination of spatial structure. The 9 RHESSI subcollimators measure the spatial Fourier component of the total source at all orientations at 9 different spatial frequencies. The frequencies are logarithmically spaced at intervals of $\sqrt{3}$ over a range that spans a factor of 81 from the finest ($2.3''$) to the coarsest ($180''$) spatial resolution. The amplitude of the modulation equals the product of the integrated flux and a function of the ratio of the size of the source to the subcollimator resolution in the same way that the response of a radio interferometer baseline depends on these quantities. A point source, or more generally, a source of dimensions smaller than the angular resolution of the collimator, will produce maximum modulation. When the source is extended, spanning more than the angular resolution of the subcollimator, the modulation amplitude declines precipitously. (For a Gaussian source of FWHM a, the log of the amplitude is proportional to $-(ka)^2$, where k is the spatial frequency of the collimator.) Thus by measuring the modulation amplitudes one may determine source sizes (Schmahl and Hurford, 2002, 2003.) This can be done for spatial scales of $\sim 2.3'' - 180''$, and as a function of energy (E=3-100 keV). Measurement of spatial scales by this method allows one to determine the sizes and shapes of both the compact primary and diffuse albedo sources, even (as in Fig. 1) when the surface brightness of the albedo is below the threshold (typically $\sim 5-10\%$) of conventional image reconstruction.

RHESSI's ability to obtain modulation amplitudes over a broad range of spatial frequencies extends the capabilities of hard X-ray imaging beyond those of HXT, Hinotori and HXIS. HXT relied on 64 fixed bi-grid subcollimators and could have, in principle, provided amplitudes from the data, but it was not done. In any case, the coarsest subcollimators (angular FWHM$\sim 30''$), were only marginally broad enough to modulate albedo emission. Hinotori used rotational modulation in a similar way to RHESSI, but had only two pairs of subcollimators, and therefore did not have enough coverage in the spatial frequency domain to isolate the albedo. HXIS used direct imaging, and did not enter the Fourier domain at all, and the low surface brightness of the source made its detection of albedo problematic. (But see Simnett *et al.*, 1981 for an inference of weak albedo emission.)

3.2 Building on preliminary work

In previous work, using the calibrated modulation profiles for a variety of flares, we have determined sizes of primary source (cores) along with estimates of sizes for albedo patches (Schmahl and Hurford, 2002, 2003). We found that the FWHM of cores of single-component 12-25 keV flares range from 3 to 10" in size. Most of the flares in this set show extended emission out to 2 to 3 times the radii of the cores, and these 'halos' contain up to 27% of the total flux.

The earlier work was based on the simplifying assumption that both the primary and albedo patch were circularly symmetric. While this may be true in many instances for the primary source during the thermal phase, it is an over simplification for the impulsive phase where the sources are usually double ("footpoint" sources), and also for the albedo patch, which from the scattering geometry (Brown and Van Beek 1975, Brown *et al.*. 1975, Bai and Ramaty 1978) is elongated parallel to the limb. Quick-look images of several thousand RHESSI flares (available on the RHESSI website) show that the median location of flares in the 12-25 keV range is close to $0.75R_{\odot}$, and therefore the elongation of the albedo patch is a normal defining characteristic. Only flares close to disk center–which are fewer in number– will have near-circular albedo patches.

4 Applications of Albedo for Scientific Questions

Preliminary work has confirmed the non-circular nature of the albedo sources. In the recent RHESSI-NESSI-II workshop (Glasgow, March 24-26, 2004), the PI showed RHESSI evidence for elongated albedo patches in several flares. Using in-phase superposed modulation profiles showed amplitude variations *vs.* roll-angle (the polar angle in the Fourier plane) that are characteristic of elongated sources, where the elongations were approximately parallel to the limb. This was in contrast to the "Cleaned" primary sources which, in the small sampled studied, were approximately round. As in the previous work mentioned above, the surface brightness of the albedo patch was found to be too small to contribute to the Clean images. This is as expected from albedo theory for source heights of $\sim 10-25\acute{}\ \acute{}$. The albedo fluxes appeared to be in the range of $\sim 10-30\%$ of the primary sources, also in the range predicted by theory.

We propose to apply the Fourier techniques to first determine the calibrated amplitudes and phases as function of spatial frequency, orientation and energy for a representative sample of flares. Expanding on the technique published earlier and outlined at the Glasgow workshop, we will use these amplitudes and phases to determine the flux, shapes, sizes, and relative positions of the albedo patches. These data will then be used for the scientific studies summarized below.

Deconvolution of X-ray photon spectra to infer electron energy spectra using the unprecedented energy resolution provided by RHESSI is on-going at many institutes. This work is important for determining low-energy cutoffs and electron energetics. An important correction to these photon spectra is the contribution of albedo. Making use of Bai & Ramaty's Monte Carlo results, Kontar *et al.* 2003) and Alexander & Brown 2002) found that adding the theoretical albedo corrections alone to a pure power-law model of the photon spectrum of the 2002 July 23 flare improved the spectral fit. This study shows how important albedo corrections are. But while Kontar *et al.* expressed the need for better albedo modeling, what is most important from the standpoint of this proposal, is to use empirically-determined albedo spectra to avoid the need for using the theoretical albedo spectrum in the first place. We will be able to determine this function empirically by measuring the relative flux of the albedo patch and comparing it to the flux of the primary source at many energies. This will provide an independent evaluation of the albedo correction deduced from theory.

4.1 Implications of albedo sources for high resolution spectroscopy

A fundamental step in using hard X-ray emission to study accelerated electrons is the interpretation of photon spectra to yield electron spectra, This step, which in essence is a deconvolution of the bremsstrahlung cross section from the observed photon spectrum is essential for addressing such issues as the nature of the low-energy electron spectral cutoff. The values of the cutoffs are keys to understanding the energetics of electron acceleration. Since the launch of RHESSI, great strides have been made in the deconvolution task (*e.g.* Kontar *et al.*, 2003 and Alexander and Brown, 2002) because of the unprecedented resolution and accuracy of RHESSI's measurements of the hard x-ray photon spectra. Nevertheless, an important facet of this deconvolution task is compensation for the albedo flux. The magnitude of this correction is very sensitive to anisotropy in the assumed electron angular distribution. (For example, downward directed electrons will produce proportionately more albedo than upwardly directed electrons.) Current deconvolution algorithms assume an isotropic angular distribution. The isolation and direct measurement of the albedo spectrum would provide, on a a case-by-case basis, an independent confirmation of the appropriateness of this assumption (and by implication of the viability of the inferred electron spectrum) and where this was not the case, a sensitive, quantitative indication of the character of the anisotropy.

4.2 Heights of primary sources

If the bremsstrahlung angular distribution is constant within a broad cone, then the height of the primary source is a simple function of the albedo patch size. Specifically, the size of the photospheric albedo patch is proportional to the square root of the height of the primary source. This is certainly useful for disk flares, where the height is completely unknown but is also of value for limb events, where it removes the uncertainty associated with removing projection effects. The ability to measure source heights is one which (for all but extreme limb flares) would otherwise would require stereoscopic X-ray data (the prospects for which are not likely until $\sim$ 2020 at best!). In some flares we will be able to use the different energy and time dependences of "footpoint" and "looptop" sources to simplify the determination of heights of each component.

What is the import of such height measurements? In the impulsive phase of flares, when it is thought that electron beams produce power-law photon spectra by thick-target bremsstrahlung, the height of the source must be a function of energy. Previous studies (Aschwanden and Brown, 2002) have found an apparent decrease in height with hardening of the power-law "foot-point" sources just inside the solar limb. This decrease is consistent with the thick-target model, but the heights inferred, 1000-2500 km, depend on the model of density-vs-height in the chromosphere. The albedo patch, if this inference is correct, should have a maximum extent of $35 - 60''$. We propose to look at the albedo patch sizes for this flare and others like it, and infer the height vs energy profile by this independent method.

In some disk flares, there may be "loop-top" or so-called "coronal" components whose coronal associations are ambiguous. Determination of the albedo patch size for the components will give better localization of the components in three-dimensional space. If the size of the albedo patch changes with time during a flare, it would be an indication that the primary source is rising or falling. Such changes might be expected if chromospheric evaporation fills up a loop while beaming from above produces bremsstrahlung.

4.3 Possible use of albedo sources for beam properties

Using the albedo patch characteristics can provide a new three-dimensional perspective on electron transport, particularly regarding departures from symmetric models of photon directivity. It has been generally assumed that photon directivity due to non-radial beaming of the bremsstrahlung-producing electrons is small. In their theoretical study, Langer and Petrosian (1977) suggested that the directivity ratio was less than 2. But empirical estimates of directivity were done using center-to-limb observations of flares, subject to many systematic errors. A more direct method, which we propose to use, is to determine the centroid of the albedo patch relative to the primary source. Asymmetry in the albedo distribution may be associated with X-ray asymmetries which can be directly attributable to asymmetry in the angular distribution of the electrons that produce the bremsstrahlung.

Information about directivity of the X-rays emitted by the primary source can be gleaned from three parameters of the flare+albedo sources: height, centroid vector and heliocentric distance)ρ). The height (h) is, as we have noted, determined from the low-k values of the profile of amplitude vs k. The centroid vector ($\Delta \mathbf{x}$), representing the transverse distance from the primary source to the albedo centroid, is known from the albedo's Fourier phase and the albedo/primary flux ratio as a function of roll angle. The heliocentric distance is determined from Clean maps of the primary source. These are all independently determined quantities, but if the primary emission is isotropic or symmetric about a vertical axis, they should be related by $\Delta x = h\ sin\rho$

We will compare Δx and $h\ sin\rho$ for a variety of flares at different longitudes, looking for discrepancies. At worst, this will place improved upper limits on the asymmetry of the photon distribution, at best, it may show asymmetries. Such asymmetries might be expected on the basis of other kinds of observations, such as that found in the ion beam distribution inferred from gamma rays (D. Smith *et al.*, 2003).

The relative magnitude of the albedo flux and the primary flux give a direct measure of the directivity. In the extreme case where the X-ray photons are directed only away from earth, the albedo patch would be the only apparent source. In the opposite extreme, the relative albedo flux would be zero. Our proposed determinations of the albedo flux relative to the primary flux will provide a new measure of X-ray directivity.

In cases where the source appears above the limb, a lower bound on the actual height is found, so one can take this height and predict the albedo patch size, and compare with observations. If the observed size is significantly smaller or stretched out in one direction contrary to that predicted from a broad cone of radiation, one may infer that there is a high degree of electron beaming. Thus albedo size, intensity, flare longitude, and source height measurement gives a handle on the electron pitch-angle distribution.

5 Method

The main method to be used in this study has already been developed for round sources, and it is partially developed for non-round sources. Basically, the method is to determine amplitudes and phases (Fourier components) from the modulated count-rate profiles. This is readily done by in-phase "stacking" of modulated count-rate profiles from successive rotations . (The software that does this will go on-line to the solar software (SSW) tree in mid 2004.) After an appropriate number of ~ 4 s rotations have been stacked, existing SSW programs are used to compute amplitudes (A) and phases (Φ). The visibility ($= Ae^{i\Phi}$) is then found for all subcollimators.

The key to extracting and using albedo is to isolate it in the Fourier plane. The radial variation in this plane (dependence on $|\mathbf{k}|$) shows the different fall-off (roughly $e^{-|\mathbf{k}|h}$) of albedo's spatial scales than the more Gaussian fall-off (roughly $e^{-(ka)^2}$)of the compact primary source. Azimuthal variations (double-peaks of A vs roll) show the characteristic elongation of albedo sources compared with the more rounded primary source. The radial and azimuthal variation of phase (Φ) provide the centroid of the albedo patch relative to the primary source.

6 Detailed Work Plan

The proposed work will proceed along the following lines. In the first year we will perform a pilot study in which we will work with a good sample of RHESSI flares for analysis and develop techniques and software. These will include the main published flares, as well as a sample of disk flares at a wide spread of longitudes and above-limb flares.

For the pilot study sample we will determine amplitudes and phases as functions of time and energy. The time integrations will be chosen to be sufficient to get good S/N ratios. From the amplitudes and phases we will isolate the albedo fluxes from the primary fluxes by using the three main characteristics of albedo (radial falloff, azimuthal peaking, and phase shifts).

For a suitable subset of flares we will compare the albedo flux-vs-energy profiles with the primary flux-vs-energy profiles to get a first order empirical measure of the albedo reflectivity function. This will be compared with published Monte-Carlo calculations.

We will use the amplitudes to determine the two-dimensional size of the albedo patches. This will then be applied to determination of heights of primary sources at a range of longitudes, and for a range of energies and for short time sequences in the impulsive phase of selected flares with good statistics.

The centroid vectors ($\Delta\mathbf{x}$) of albedo patches will be inferred by fitting the amplitude profiles with a simple model (see Appendix for details). The primary heights (h) and heliocentric distances (ρ) will provide the predicted centroid vector, $h\ sin\rho$, to be compared with the inferred $\Delta\mathbf{x}$. Differences between these quantities will be assessed statistically to identify any directivity in the downward X-ray flux.

For flares with external estimates of height (above limb) we will look for discrepancies in the height determination method. For disk flares we will look for discrepancies in the predicted albedo patch axial ratio and orientation as a function of disk position. Such discrepancies, if they pass statistical tests, may be evidence for anisotropic directivity and/or beaming.

If any flares found in the initial selection phase cannot be mapped by straightforward imaging methods, they will be assessed to see if their albedo carries the bulk of the flux. Such flares would be dominated by downward X-ray directivity, and would be flagged for further analysis.

By the second year of the study, we will have automated most of the processes for the determination of the quantities described above. Thus we will be able to extend the work to a much larger number of flares, and turn the focus of the study in the directions of most interest found in the first year.

7 Development of Useful tools

As part of this project, we will be developing, testing and posting software tools for source size measurement of primary sources. These will be generally useful for quantitative determination of flare sizes, needed for determination of electron densities and energies in many other studies by the solar community.

We will also be developing software tools to use higher harmonics of the modulation phases. At the present time, as discussed by Hurford, Schmahl *et al.* (2002), RHESSI users only make use of the fundamental component of the subcollimator profiles. In principle, it is possible to fit the quasi-triangular grid and collimator profiles with a series of sinusoids including up to the third harmonic. For stronger flares, the addition of the 2nd and 3rd harmonics will provide measurements at additional spatial frequencies and fill in the gaps between the 9 fundamental spatial frequencies. This will improve size profile determination for both primary and albedo sources, with improved imaging as a by-product. This generally useful capability, already partially built into the imaging software, will be provided to the user community.

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8 Organization of Work

The PI (E. Schmahl) will identify flares for study. covering a wide range of longitudes, energy bands, and spatial characteristics, expand tools for Fourier characterization of albedo locations, sizes and spectra. He will apply these tools in conjunction with his scientific collaborator (G. Hurford). Papers produced will be co-authored with other solar scientists who have theoretical or previous interest in the flares studied.

Scientific collaborator G. Hurford will handle instrumental response matters, *e.g.*, grid response issues, inter-detector sensitivities, top-down tests, harmonics and self-calibration methods.

The first year of effort will be a pilot study focusing on a representative sample of the flares, for which the amplitudes and phases will be found. In the first year, only representative times for calculation of albedo will be chosen, but all stages of the work identified in the summary will be targeted.

In the second year of effort, using the experience gained in the first year, the project will be extended to a much larger sample of flares. to improve the statistics on center-to-limb effects, and to add focus on the flares of most interest to the solar community. The same stages of work in the summary above will be performed, but with greater emphasis on the variability of flares.

9 Personnel

The PI (E. Schmahl) has been studying the Sun using Fourier methods in radio (Culgoora, Clark Lake, Westerbork, OVRA, and the VLA) since 1970. He became involved in hard X-ray spectroscopy during SMM in the 1980's and began applying Fourier techniques to solar flares with HEIDI and the steps leading to RHESSI. He has collaborated with Hurford in several HXR imaging projects, and with many others in multi-wavelength studies of solar flares. Currently he works with the RHESSI team at GSFC as the PI for a grant to the University of Maryland for flare research.

Scientific collaborator G. Hurford is one of the originators of the RHESSI imaging concept. He has been involved in the definition of Fourier type imagers for hard X-rays since the proposals for P/OF, SAC-I, GRID, Grid-on-a-balloon, HEIDI, HESI, and finally HESSI/RHESSI. His long experience in radio interferometry at Caltech and Berkeley (OVRO, VLA, and FASR) has given him a good understanding of the Fourier methods. He is presently at SSL, UC Berkeley, working with the RHESSI team.

10 APPENDIX

Separating out the albedo from primary sources in RHESSI data

Figure 2 (red curve) shows the observed amplitude profile vs spatial frequency (k) for a typical RHESSI flare. The black curves show attempts to fit the amplitude profile with Gaussians and exponentials. The first panel shows the failure of Gaussians at the smallest spatial frequencies (corresponding to RHESSI's subcollimators 6,7,8, and 9. The dashed curves show good fits at high spatial frequencies (corresponding to RHESSI's subcollimators 2,3,4, and 5) using Gaussians.of reduced amplitude. The inset shows the Clean map of the primary source, which has a near Gaussian profile. Since the Fourier transform of a Gaussian is a Gaussian, and the Cleaned source is Gaussian, this map is consistent with the fit shown by the dashed curves. But clearly more than the one component shown by the Clean map is required, and that is given by the low-frequency part of the steeply-falling amplitude profile.

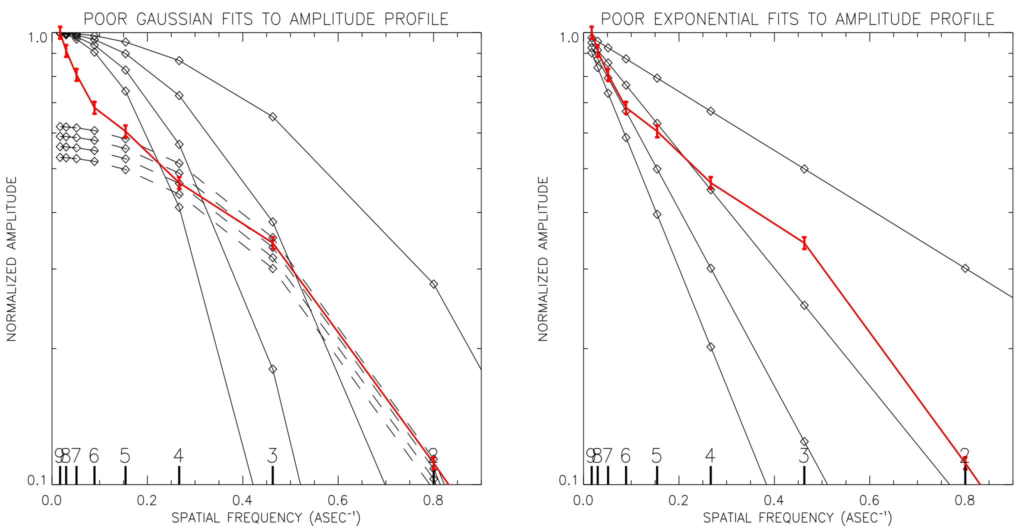

Figure 2: Demonstration that an observed RHESSI amplitude profi le requires multiple components for a good fi t. The red curve in the fi rst panel shows the observed amplitude profi le vs spatial frequency (k) for the 2002 August 30 flare. The shape is clearly non-Gaussian at the smallest spatial frequencies (sub-collimators # 6,7,8,9 as indicated on the abscissa). But at the higher spatial frequencies (sub-collimators # 2,3,4,5), as the dashed curves show, the profi le can be fi t by a Gaussian. The inset shows a Clean map of the primary source, which appears to be Gaussian. The second panel shows that a linear fi t (m=slope) is good at lower spatial frequencies, but bad at higher spatial frequencies. The error bars are set to an (arbitrary) 3%.

In the second panel, the solid curves show exponential fits to the observations (red curve). It is possible to fit the low-spatial-frequency data (subcollimators 6,7,8, and 9) with an exponential (straight lines on this log amplitude vs k plot), but the fit at higher spatial frequencies is totally inadequate, indicating that the model must have multiple components. This poor fit at the lower spatial frequencies was found for all the flares studied by Hurford and Schmahl (2002,2003), and Schmahl (2004), and undoubtedly it is a general property of flares.

But what is the physical interpretation of this linear falloff of log(amplitude) vs k shown in the second panel above? That is, what brightness distribution corresponds to this amplitude function? The answer is that is a good approximation of an isotropically back-scattered albedo patch. The exponential e^{-kh} happens to be the Fourier transform of $h^3/(h^2+r^2)^{3/2}$, which is Brown's (1975) albedo patch distribution. Thus one can find the strength of the albedo in the presence of the primary flux by using the appropriate combination of an albedo function and the primary source and fitting it to the observations.

For a primary source that can be modeled in the Fourier plane by a simple function $G(\mathbf{k})$ and an albedo patch modeled by another function $A(\mathbf{k})$, a linear combination of the two is sufficient to model a wide class of possible amplitude distributions. The only other quantity required is a phase-shift term, $e^{i\mathbf{k}\cdot\Delta\mathbf{x}}$, to account for the spatial displacement between the centroid of the albedo patch and the projected position of the primary source. The albedo patch is produced by a convolution with the primary source. In the Fourier plane convolution reduces to a simple multiplication, so the primary contribution G(k) appears as a multiplicative factor.

$$V = [c_1 * A(k) e^{i\mathbf{k}\cdot\Delta\mathbf{x}} + c_2] G(k) \qquad (1)$$

This is the technique which we propose to use for isolating the albedo patch from the combined amplitudes and phases of the primary source and the back-scattered albedo patch. Figure 3 shows the amplitude profile vs spatial frequency for the same flare as Fig. 2. As before, the subcollimator numbers for 8 spatial frequencies are marked along the abscissa. We have have excluded subcollimator 1 (k = 1.4 asec^{-1}) because it gives amplitudes too small to be trustworthy.. To characterize the albedo and the primary source, we assume a simple model containing 5 parameters, and fit the model to the amplitude profile. The parameters are:

- F_0: Total Flux
- F_{alb}: Relative flux of the albedo
- h: Height of the primary source above the photosphere
- a: Gaussian half width of the primary source
- Δx: Projected displacement of the centroid of the albedo patch.

The model consists of the 2-D Fourier transform of an elliptical albedo patch. For a circular patch, this would be proportional to $(h^2+r^2)^{-3/2}$ for isotropic scattering (Brown 1975). The Fourier transform of this function is a simple exponential $exp(-kh)$. For the general case, where the albedo appears at an arbitrary longitude, the function must be appropriately "fore-shortened". There is also possible truncation by the limb (not required for this flare). The shape of the primary source is modeled by a circular Gaussian as suggested by the Clean map seen in the inset of Fig. 2.. The functional form to be fitted to the data is then given by a parametric version of equation (1).

Figure 3 shows fits to the observed profile (red curve) varying each parameter separately about the best fit. These curves show that there is considerable independence of the parameters in parameter space, and that their effects are well separated.

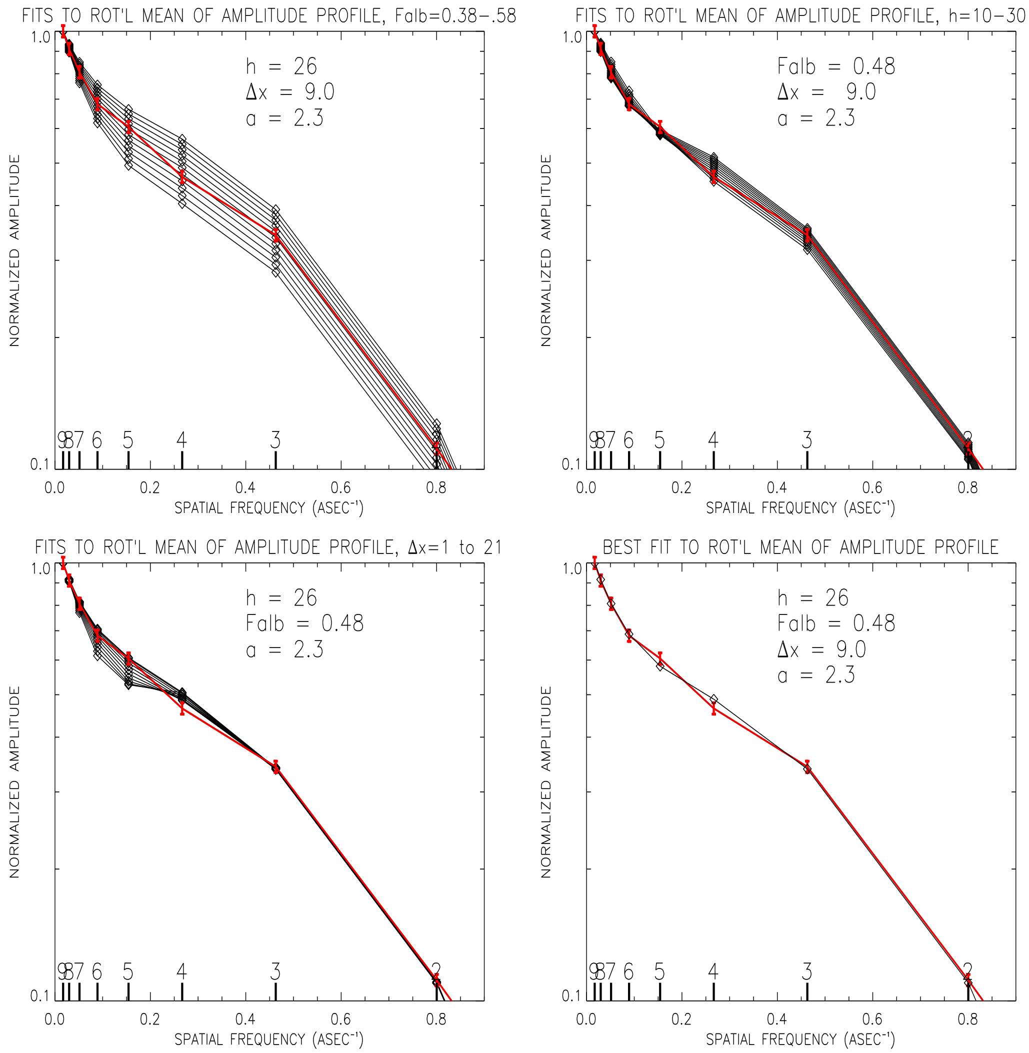

Figure 3: Example of fitting an observed RHESSI amplitude profile (the flare of August 30, 2002).. The amplitudes (red curves) of the modulated X-rays were computed from phase-calibrated data. This profile of amplitude vs spatial frequency (k) was rotationally averaged, and a rotationally-averaged 5-parameter model was fitted. The Gaussian half width of the source was readily fit to the finer subcollimators (# 2,3,4,5). Ranges of fits to the other parameters (F_{alb}, Δx, and h) are shown with only the best fit shown in the last panel. The profile fits are all normalized to 1 by a constant F_0 at the smallest k.

In general it is possible to use the amplitudes at arbitrary roll angles ϕ, and this can allow us to determine more parameters, as might be necessary for double sources, which normally occur during the impulsive phase ("footpoint" sources). Fitting a model to several (5-10) ranges of ϕ would make it possible, for example, to determine the direction of the displacement $\mathbf{\Delta x}$ of the albedo centroid, which should be radial if the primary X-rays are isotropic. Departures from the radial direction would indicate directivity, which then could be quantified.

BUDGET AND MANPOWER
5/15/2005 - 5/14/2007
PROJECT: A Study of Solar Hard X-ray Albedo Sources

		1ST YEAR	2ND YEAR
I.	Personnel		
	E. Schmahl, P.I., 6 mos. effort:	$00,000	$00,000
	G. Hurford, No charge to grant		
II.	P.I. Benefits	$00,000	$00,000
	Total Salaries and Fringes:	$00,000	$00,000
III.	Other Direct Costs		
	Supplies/Hardware	$000	$000
	Publications, Page Charges (5 pages)	$0,000	$0,000
	Domestic Meeting,	$0,000	$0,000
	Total Direct Cost:	$00,000	$0,000
IV.	Indirect Cost (28% of T.D.C.)	$00,000	$0,000
	Total 1st/2nd Year Costs:	$00,000	$00,000

BUDGET JUSTIFICATION

The budget for this proposal assumes that the PI will work half-time on the proposed effort at NASA Goddard Space Flight Center. The other half of his time, also at GSFC, will be supported separately from the RHESSI funds provided to the Goddard RHESSI team. The unfunded Scientific Collaborator, Gordon Hurford, will collaborate electronically from his home institution at Space Sciences Lab, UC Berkeley, to ensure that instrumental response matters of the proposed work are handled correctly.